SANDIA NATIONAL LABORATORIES
CIVILIAN RADIOACTIVE WASTE MANAGEMENT OFFICE OF
SCIENCE & TECHNOLGY and INTERNATIONAL PROGRAM

Test Plan 04-01

Testing the Concept of Drift Shadow with X-Ray Absorption Imaging Experiments

Revision 0

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Author:	*Original Signed by Susan J. Altman* Susan J. Altman	Date:	05/13/2004
Author:	*Original Signed by Clifford K. Ho* Clifford K. Ho	Date:	05/13/2004
Review:	*Original Signed by Ray E. Finley* Technical Reviewer, Ray E. Finley	Date:	05/13/2004
Review:	*Original Signed by Thomas Lowry* Technical Reviewer, Thomas Lowry	Date:	05/13/2004
Concurrence:	*Original Signed by Martha J. Mitchell* QA Reviewer	Date:	05/13/2004
Approval:	*Original Signed by Hong-Nian Jow* SNL OSTI Project Lead	Date:	05/13/2004

REVISION HISTORY

Rivision No.	Effective Date	Description of Change
0		This is the original version of this test plan; no prior revisions exist.

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1. PURPOSE AND SCOPE

The objective of the work described in this Test Plan (TP) is to evaluate the concept of the drift-shadow effect in Yucca Mountain through X-ray absorption laboratory visualization experiments. Current Performance Assessment models show that capillary effects will divert water around the drifts. This effect has the potential to limit the amount of flow available to transport radionuclides directly beneath the drifts.

Our understanding of this conceptual process will be improved through laboratory experiments. X-ray absorption imaging (Tidwell and Glass, 1994; Tidwell et al., 2000, Altman et al., 2004) is an experimental technique that allows for the visualization and quantification of transport through geological media. These experiments will be used to provide physical and visual evidence to evaluate the drift-shadow phenomena.

The specific objectives of these X-ray absorption experiments are:

- Provide a quantitative evaluation of the percentage of diversion around a drift due to the drift shadow effect
- Provide visual evidence of where percolating water travels in the vicinity of a drift in a fractured tuff system
- Provide comparisons to model predictions to better understand the performance and limitations of current modeling approaches

The ultimate goal of these studies is to provide a basis for assessing the conservatism of current performance-assessment models that use the total percolation flux in the radionuclide transport calculations at the repository horizon. These studies may show that only a fraction of the total percolation flux is available for transporting radionuclides immediately beneath the repository.

1.1. Major Activities and Products

Major activities in the experimental analysis include:

- Construction of test cells
- Scoping analysis in support of experimental design
- Conducting X-Ray imaging experiments
- X-ray imaging experiment data analysis
- Interpretation of the experiments and comparison to model predictions

There will be two rounds of experiments. The first round (FY04) will use rocks samples that are not in the Q management system. These samples have been collected from Yucca Mountain. Appropriately managed samples will be used for any Q-experiments, intended for FY05. Completion of data analysis from these experiments, completion of

numerical analyses, and documentation of the results of the project will be performed in FY06.

Note that scoping analyses will be conducted in support of the experimental design and numerical implementation testing. Pre-test predictions will not be performed.

2. EXPERIMENTAL PROCESS AND DESCRIPTION

2.1. Experimental Approach

X-ray absorption imaging is a powerful method for obtaining quantitative measurements of fluid flow and solute transport in two dimensions with pixel sizes on the sub-millimeter scale (Tidwell and Glass, 1994; Tidwell et al., 2000; Altman et al., 2004). We intend to use this methodology for two purposes: 1) provide visual evidence of the drift shadow effects, and 2) provide quantitative estimates of the percentage of diversion around the drift due to the drift shadow effect.

Two-dimensional, rectangular test cells on the scale of approximately 10 cm x 15 cm x 2.5 cm will be constructed. Each test cell will have a small-scale drift cored out of the rock sample. Three or four test cells will be created for each round of experiments. Different materials and different arrangements of fractures in relation to the drift will be used to examine matrix-only flow, fracture-matrix, matrix-drift and fracture-drift interactions. Schematics of possible test-cell configurations are shown in Figure 1.

The sample will initially be saturated with a high-concentration KI solution. Although in reality the matrix is not saturated, average values of saturation measurements from core samples have ranged from 72% - 85% (Flint, 2003). Maintaining a constant saturation level below full saturation would be quite complicated. Instead we have opted for keeping the matrix saturated.

A KI-free tracer will be introduced onto the top of the test cells as the upper boundary condition. It is most likely that the water will be dripped onto the top of the sample at an approximately constant rate. This method would approximate a dripping fracture. The water would drip at several locations along the upper boundary. X-ray images will be collected as a function of time in order to visualize and assess the movement of the tracer in the test cell. X-ray imaging will allow for the measurement of tracer concentration as a function of time at the sub-millimeter scale. At the same time, samples will be collected along the bottom of the test cell. The aluminum frame on the bottom of the test cell will be constructed with separate sample ports so that we can laterally differentiate where the water is flowing. The volume of water along the bottom of the flow cell will be measured to determine if there is more water being discharged away from the drift than directly under the analog drift. Water samples will also be collected in the drift so that we can complete the water balance and determine how much water is dripping into the drift and how much water is held in the matrix. Concentration of the tracer in the samples will be measured to assess the mass flux out of the system.

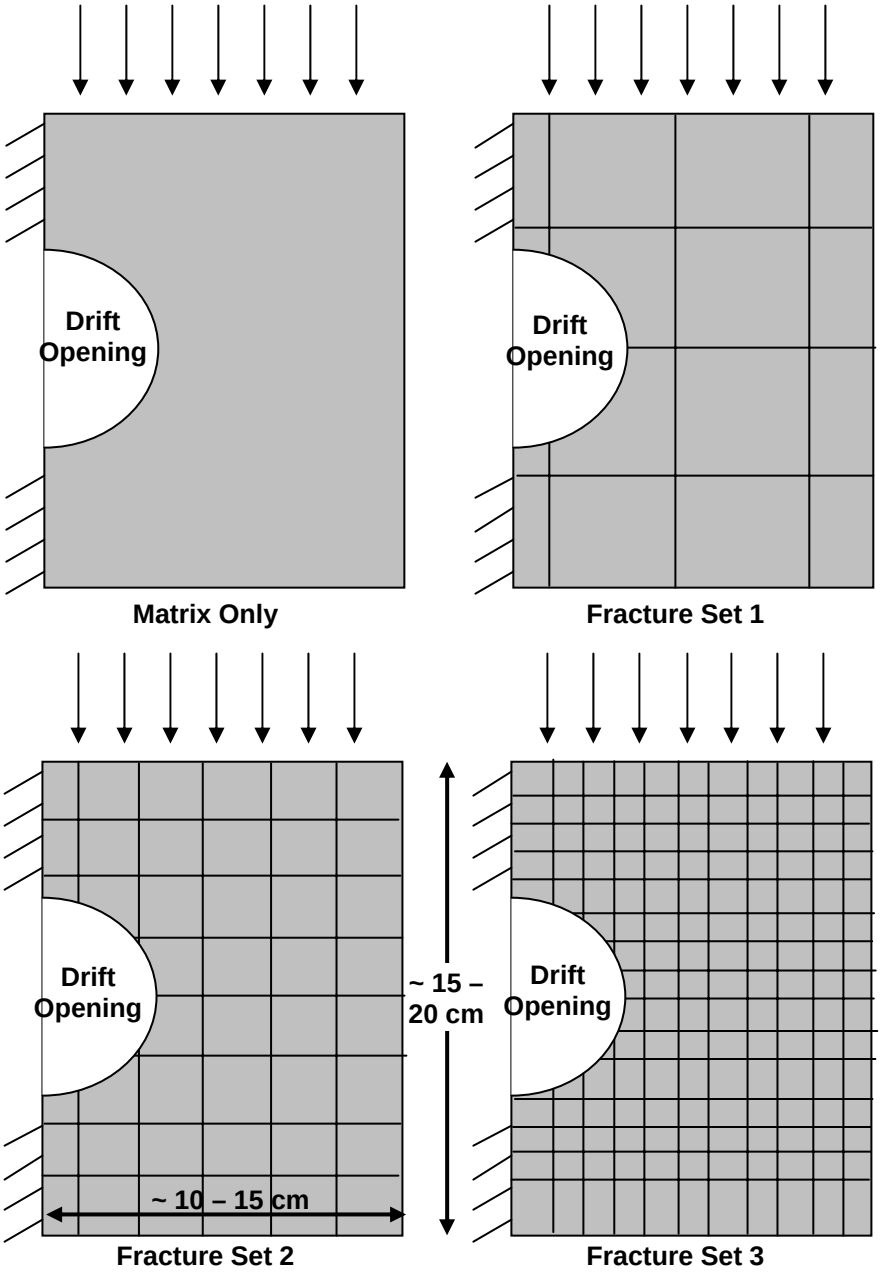

Figure 1: Schematic of draft test-cell design.

2.1.1. Sample Selection and Preparation

Pre-existing slabs of tuff obtained from Yucca Mountain will be used to construct the test cells for the FY04 experiments. These slabs were obtained before the current QA program was developed and thus should be considered non-Q. Future experiments will be conducted using Q-samples. The slabs will be cut to the appropriate size

(approximately 10 cm x 15 cm) and ground to a uniform thickness of around 2.5 cm. Scoping calculations will be performed to determine if these dimensions are appropriate to facilitate experiment durations that do not exceed several months. The final dimensions of samples used in the experiments will be measured with electronic digital calipers. The drift and fractures will be machined in the sample prior to placement in the test cell frame.

Each sample will housed in a separate test cell. Four bars of aluminum will be cut to fit around the four edges of each sample. The frame is used to provide rigidity to the test cell, minimize X-ray scatter around the edges of the sample, and provide no-flux boundaries. The upper bar will be constructed so to allow for the dripping upper boundary condition at different locations along the top of the sample. The lower bar will be constructed so that we can collect samples at different locations along the bottom boundary. The rock samples will be set into the aluminum frame. The frame and samples will then be encased in epoxy. The epoxy will be used to form no flux boundaries along the faces and edges of the sample. A high viscosity epoxy will be used to minimize imbibition into the rock. Clear contact paper will be sealed over the fractures and drift hole prior to sealing with epoxy to ensure the epoxy does not fill these regions. A sampling portal will also be set into the drift area so that water seeping into the drift can be collected.

2.1.2. X-Ray Absorption Imaging

X-ray images will be acquired at selected time intervals throughout the experiment in order to visualize the movement of the tracer through the test cell and measure the normalized tracer mass throughout the test cell. It is most likely that more images will be collected at the start of the experiment. We will use the scoping analyses to determine when images should be collected. High-resolution, X-ray absorption images are acquired by directing a beam of X rays at the face of the test cells while recording the transmitted X rays on film secured in a cassette behind the test system. The X-ray source, a MG-161 constant potential x-ray system utilizing a Phlips MCN-165 end-grounded, metal-ceramic x-ray tube, will be located a sufficient distance from the film to expose the entire film while minimizing parallax. X-ray source parameters used in imaging will be tuned to the absorption characteristics of the tracer (KI). It is most likely that a source intensity of 60 kV at 27 mA will be used, based on previous experiments. The accompanying exposure time will be determined by trial-and-error to maximize image contrast, which is a function of sample thickness and tracer concentration.

Digitizing of the X-ray film is necessary to quantify the information from the experiments, namely the spatial variation in mass of solute in the samples as a function of time. The amount of X rays transmitted through the sample is, in part, dependent on the solute mass. The digitizing process produces gray-level light-intensity values at a pixel scale. The more X rays that are transmitted, the darker the X-ray film, and therefore the lower the gray-level intensity recorded when digitizing the film. Digitizing will be accomplished by one of two methods. For the first method, the exposed X-ray film is placed in front of a diffused bank of high-frequency (60 MHz), high-output fluorescent

lights. A computer-controlled feedback loop will be used to maintain consistent light intensity during imaging. Variation in the transmitted light intensity field will be recorded by means of a charge-coupled device (CCD) camera focused on the front of the X-ray film. For the second method, the film is digitized by a scanner. To obtain gray-level values for one piece of film, 50 images will be acquired by the CCD camera and averaged. This averaging is done to reduce the random error produced by CCD signal noise (Detwiler et al., 1999). In previous experiments where the CCD camera was used to digitize the film, pixels sizes ranged from 0.25 mm on a side (Tidwell et al., 2000) to 0.3 mm on a side (Altman et al., 2004). The pixel size could decrease of the film is digitized using the scanner.

2.1.3. Experimental Data Analysis

2.1.3.1. Porosity Estimates

The porosity ($\phi_{i,j}$) at each pixel is determined from the X-ray images taken of the tracerless (I_d) and tracer-saturated (I_s) samples. The natural log transformed images are subtracted and then normalized by the mean value and scaled by the bulk porosity:

$$\phi_{i,j} = \frac{\ln(I_s)_{i,j} - \ln(I_d)_{i,j}}{E\left[\ln(I_s)_{i,j} - \ln(I_d)_{i,j}\right]}\phi_{bulk}\frac{z_{i,j}}{z_{avg}} \quad (1)$$

where $E[\ln(I_s)_{i,j} - \ln(I_d)_{i,j}]$ is the average difference between the tracer saturated and tracerless images, ϕ_{bulk} is the bulk porosity of the rock slab, $z_{i,j}$ is the thickness of the slab at point i,j, and z_{avg} is the average thickness of the rock slab. As the samples will be ground to have an even thickness, the $z_{i,j}/z_{avg}$ term drops out of the equation.

The bulk porosity is estimated by calculating the change in mass between the dry samples and saturated sample as follows:

$$\phi_{bulk} = \frac{\left(M_{sat} - M_{dry}\right)}{\left(\rho_{tracer} V\right)} \quad (2)$$

where M_{sat} is the mass of the saturated sample, M_{dry} is the mass of the dry sample, ρ_{tracer} is the density of the tracer and V is the volume of the sample.

2.1.3.2. C/C_o and M/M_o Estimates

Relative concentration is calculated from the adjusted gray-level images by applying linear absorption theory (Tidwell and Glass, 1994). Specifically, at each point or pixel in the image domain the following equation is applied:

$$\frac{C}{C_o} = \frac{\ln(I) - \ln(I_d)}{\ln(I_s) - \ln(I_d)} \tag{3}$$

where I is the transmitted light intensity at a fixed point, I_s is the transmitted light intensity at the same point on the image for the fully tracer-saturated condition (image $C/C_o = 1$), and I_d is the transmitted light intensity at the same point on the image before the sample has been saturated with tracer, the dry image, (image $C/C_o = 0$).

The normalized cumulative mass (M/M_o) is calculated as follows:

$$\left(\frac{M}{M_o}\right) = \frac{\sum_{i=1}^{N}\left(\frac{C}{C_o}\right)_i z_i \phi_i}{\sum_{i=1}^{N} z_i \phi_i} \tag{4}$$

where M is the mass of tracer in the area at the time the X-ray image was taken and M_o is the corresponding quantity when the sample is saturated with tracer, z_i is the thickness of the slab at a given pixel, ϕ_i is the corresponding porosity and N is the number of pixels in the area.

2.1.3.3. Flux Measurements

Water samples will be collected at different lateral locations along the downstream side of the sample. In addition, water that has seeped into the analog drift will be collected. The weight of the discharge water as a function of time and location will be measured. In addition, the iodine concentration can be measured to determine mass flux.

2.1.4. Potential Sources of Error

Sources of error can be divided into error associated with running the experiment and image analysis error. Experimental error include errors associated with not completely saturating the samples, sample volume measurements, leaks from the system, and movement of the X-ray head.

If the samples are not completely saturated, the bulk porosity of the sample may be under estimated. Errors in bulk porosity measurement will not effect the relative concentration distributions and will only have a minimal effect (if any at all) on the relative mass estimates (Section 2.1.3.2). As the samples being used in this experiment are relatively porous, we believe that we will be able to fully saturating the samples. If there are doubts in our bulk porosity estimates, we can measure porosity of the matrix after the experiments are completely using a different method (e.g., helium porosimetry) and adjust our bulk porosity measurement accordingly.

There are also potential errors in the calculation of the total volume of the samples. We will assume that the samples are rectangular blocks. This assumption is mostly valid because of the careful sample preparation. Several dimension measurements will be to ensure that the measurements are consistent. However, it is possible that there will be minimal chipping along the edges of the sample. Thus the assumption of rectangular blocks leads to an overestimate of the sample volume. This error only effects the porosity estimates.

Another source of experimental error is leaks from the system. All efforts will be made to minimize or eliminate any leaks. Any leaks that are observed will be noted. To evaluate the effects of the leaks, comparisons can be made between the information obtained from the X-ray data (which could potentially overestimate mass loss due to diffusion) and information obtained from the recovered mass in the outflow solution (which could potentially underestimate mass loss due to diffusion).

Movement of the X-ray head during the course of the experiment could also be a source of experimental error. Each time images were taken for these experiments care will be taken to ensure the X-ray head is in the original position so that the intensity of the images will remain consistent. Errors from X-ray head movement can be partially corrected with the wedge analyses. The wedge error analyses captures this error along with others discussed below.

Potential sources of image-analyses errors include image registration, CCD camera or scanner noise, and variations in the light-source intensity, X-ray source intensity, and the film developing process. To assist with film registration lead reference points will be affixed to each rock sample. Image registration is accomplished manually, with the assistance of a computer program that minimizes the least-squared difference in distance of these markers. This process allows for the registration of the images within less than $1/10^{th}$ of a pixel. The epoxy wedge will be used to correct for temporal variations in the light source intensity and film developing variations. Evaluations of the errors have shown that the errors can be reduced to 3% or less (Tidwell, personal communications).

2.1.5. Product of Experimental Work

The experimental work will provide the following products:

- Images of the test cells showing where the percolating water is traveling through the cell, in relation to the drift
- Quantitative data on the relative concentration of dripping water throughout the test cell as a function of time and location
- Quantitative data on the mass flux and/or volumetric flux through the system.

2.2. Sample Control

There are two types of samples generated from this experimental work. First are the rock samples that will be put into the test cells, as described in Section 2.1.1. Second are the

outflow samples that will be collected during the experiment. Sample control for the work under this test plan will follow the Sandia National Laboratories', OSTI Procedure QAP 13-1. Each sample will be appropriately labeled. Sample preparation, utilization, and final disposition will be documented in scientific notebooks. When samples are not in the possession of the individual designated with their custody, they will be stored in a secure area with associated documentation (chain of custody) (with the exception of non-Q samples).

No special sample storage methods are needed for the rocks samples. Samples of outflow solution may be saved in order to measure iodide concentrations (see Section 2.3). Outflow solution samples may be kept in sealed containers under refrigerated conditions. The hold times of the samples before analysis (if conducted) will be recorded.

2.3. Data Quality Control

Measuring and Test Equipment (M&TE): Table 1 lists the M&TE employed for the experiments described in this test plan along with their intended use. Measurement controls pertaining to each instrument or instrument system are given in the Data Acquisition Plan (below). Details of specific instruments used (e.g., make, model, serial number, and calibration information) will be documented in the records for each testing round. A calibration program will be implemented for the work described in this test plan in accordance with QAP 12-1, "Control of Measuring and Test Equipment." In addition, QAP 13-1 identifies requirements and appropriate forms for documenting and tracking sample possession.

Data Acquisition Plan: Two basic data types will be generated as part of this program. The first general set is termed supporting data and includes rock matrix properties, tracer concentrations, time, fluid/rock mass, rock dimensions, physical descriptions, and aqueous diffusion coefficients. Measurement and test equipment (M&TE) used to acquire these data are identified in Table 2. Calibrations for M&TE will be provided by the SNL Measurements Standards Program (MSP) unless otherwise indicated

The second set of data corresponds to the test data and includes acquired X-ray images and image analysis. A description of the data, source, software, format, and data verificaton/maintenance process is provided in Table 3.

Data and calculations will be recorded electronically, in scientific notebooks, on data sheets or logs, or by other appropriate means as described in the records package for each test phase.

Data files stored on electronic media will be backed up at least every 60 days. The backup files will be maintained in a location separate from the original files.

2.4. Data Identification and Use

The steps required to process the image-based data are identified in Section 2.4, Table 3. The accuracy and traceability of data transfer, reduction, and analyses will be accomplished as follows:

- Sample identification and control will be maintained in accordance with QAP 13-1 Sample Control. Samples or sample containers will be labeled with a unique sample identification number. In addition, samples may be photographed. Sample numbers will be documented as part of the records for each testing phase. Abbreviated sample identification numbers will be traceable to the original sample identification number.

Table 1. List of Measurement and Test Equipment

Description	Use
circular rock saw or band saw with diamond cutting blade	cut test specimens from rock core
surface grinder with diamond grinding wheels	grind test specimens to final dimension
vacuum pump connected to a vacuum chamber	vacuum saturate test specimens
X-ray imaging system	visualize and quantify diffusion process
clock	record time for each X-ray image
ion-specific probe	measure input and output tracer concentration
analytical balance	weigh specimens and brine/tracer circulated through each sample
weight set	time-of-use calibration of analytical balances
calipers	measure dimensions of each sample
micrometer end standards	time-of-use calibration of calipers
specimen test cell	maintain known and constant boundary conditions on all surfaces of the rock specimen
fluid delivery system	drip water along the top of the test cell

- The traceability of input and output files will be maintained and documented through all steps of data processing.
- Routine calculations performed by scripts and codes will be documented and verified.
- Manually input data used in calculations performed by software will undergo spot or random checks for accuracy. These checks will be documented.
- Manual calculations will be documented, including checks of these calculations.

- The Region of Interest (ROI) (that is regions within the digitized images where calculations are being made) used in processing images will be documented.

Data will receive a technical review by the PI or designated representative and QA review for completeness. The review period for scientific notebooks will be documented in each scientific notebook. Scientific notebooks will be reviewed by an independent technical reviewer at least semi-annually. Data that are unsuitable for use will be clearly identified and the reason for rejection of the data shall be stated.

Table 2. Measurement of Support Data

Data	Acquisition Method	Units	Format	Allowable Error	Error Control Measures
Time since start of experiment	Digital or analog clock	date: hr: min	Manually read clock	±15 minutes Accuracy will not be verified by the SNL Measurement. Standards Program (MSP)	Perform independent check of calculations. Clock will be periodically checked against another clock.
Tracer concentration in outflow	TBD (e.g, ion-specific probe or ion chromatograph)	mg/L	Measurements could be made with an ion specific probe or an ion chromatograph.	±10.0%	Implementation of technical and QA requirements as specified in contract
Matrix Porosity	TBD (e.g., helium porosimetry)	%	May take core samples out of slabs for verification of porosity measurements.	±1%	Implementation of technical and QA requirements as specified in contract
Physical description of samples	visual inspection	NA	Manual record maintained.	NA	Independent review of notes
Fluid and Rock Mass	analytical balance	grams	Balances are read manually	±0.01 g	Time-of-use checks using calibrated weight set
Length	digital or analog caliper	cm	Calipers are read manually.	±0.01cm	Time-of-use checks using calibrated gages

Separate analysis notebooks will be kept for the modeling and analysis component of this project. An independent technical reviewer will review these notebooks at least semi-annually. The review period will be documented in the analysis notebook.

3. MODELING AND ANALYSES

3.1. Introduction and Objectives

Models of liquid flow through porous and fractured rock with a confined cavity will be developed using analytical and/or numerical methods. The objectives are to (1) provide scoping calculations to aid in the design and execution of the experiments and (2) compare predictions to experimental results to gain confidence and/or understand limitations of current modeling approaches that simulate capillary diversion around an opening. The type of models and analyses performed in this study are designated as Programmatic Decision, per QAP 9-1.

The scope of the modeling and analyses will be focused on simulating the processes that occur in a fabricated two-dimensional test cell described in Section 2. Figure 1 shows

Table 3. Image Based Data

Step	Data	Source	Software	Format	Data Verification/ Maintenance
1	X-ray image	X-ray intensity field transmitted through sample	None	film	Record transmitted X-ray intensity field on film. Following exposure, film is developed using an automatic film developer. Developed film will not be submitted as a record because the film degrades over time.
2	digitized X-ray image	developed X-ray film from step 1	OFF-THE-SHELF image processing software (potentially IP Lab, Version 3.92)	array of gray-level values	Pass light through X-ray film and digitize transmitted light intensity field into an array of gray-level values. Care must be taken to achieve proper image registration. Data maintained electronically. Software performs routine calculations. Calculations will be documented per QAP 9-1.
3	reference film density	digitized X-ray image from step 2	OFF-THE-SHELF software (potentially KaleidaGraph, Version 3.6)	polynomial coefficients	Fit polynomial function to gray-level wedge thickness curve measured for each X-ray image. Data maintained electronically. Software performs routine calculations. Calculations will be documented per QAP 9-1.
4	adjusted X-ray image	digitized X-ray image from step 2 and wedge data from step 3	In-house FORTRAN code	array of gray-level values	Using information from constant density wedge, adjust each image for variations induced by film developing process, etc. Data maintained electronically. Software performs routine calculations. Calculations will be documented per QAP 9-1.

5	porosity	adjusted X-ray image from step 4	OFF-THE-SHELF image processing software (potentially IP Lab, Version 3.92)	ϕ	Using adjusted X-ray images, employ linear absorption theory (Equation 1) to porosity. Data maintained electronically. Software performs routine calculations. Calculations will be documented per QAP 9-1.
5	relative tracer concentration	adjusted X-ray image from step 4	OFF-THE-SHELF image processing software (potentially IP Lab, Version 3.92) and in-house FORTRAN code	C/C_o	Using adjusted X-ray images, employ linear absorption theory (Equation 1) to calculate relative tracer concentration. Data maintained electronically. Software performs routine calculations. Calculations will be documented per QAP 9-1.
6 (optional)	colorized relative tracer concentration and matrix porosity images	relative tracer concentration image from step 5 and matrix porosity image from step 6	OFF-THE-SHELF image processing software (potentially IP Lab, Version 3.92)	C/C_o	Using relative tracer concentration data, falsely colorize images according to a consistent scale. Data maintained electronically. Software performs routine calculations. Calculations will be documented per QAP 9-1.

some potential configurations of the test cell, which is on the order of several tens of centimeters in length and width.

Potential sources of uncertainty include the material property and other parameters that are used in the models. Properties that can be measured directly from the test-cell samples will be used when available, and constitutive relations and values that are not readily measured will be taken from the literature for comparable materials. Conceptual models of flow through fractures is another source of uncertainty, but the focus will be on using conceptual models that are currently used on the project. Comparisons between simulated and experimental results will be made to evaluate the current modeling approaches. Numerical errors are also potential sources of uncertainty, and, if time permits, different mesh resolutions will be investigated.

3.2. Approach

Analytical methods will assume an effective continuum that represents the matrix (with or without fractures) surrounding the opening. Numerical methods will use effective continuum and/or dual-continuum approaches to represent the domain surrounding the opening. Material properties and constitutive relations will be obtained from laboratory testing and/or available literature.

A sketch of the proposed 2-D test cells is shown in Figure 1. Water is introduced at the top of the test cell and allowed to flow downward through the matrix and fractures. Additional information regarding the experimental tests is provided in Section 2. For the numerical simulations, the upper boundary will be a specified flux or water pressure, while the lower boundary will be a specified pressure to allow free drainage. The sides will be no-flow boundaries. The initial condition will be a gravity drained (hydrostatic)

condition in the test section. A steady-state flow simulation will be performed, and particle-tracking may be simulated to visualize the flow paths. The flow distribution along a horizontal plane beneath the opening will be evaluated.

3.3. Software List

Software and codes that may be used to conduct the modeling and analyses in this study include the following:

- TOUGH2: Flow simulations
- DCPT: Particle tracking
- Mathcad: Analytical and semi-analytical solutions

3.4. Tasks

The following is a list of the primary tasks to be completed as part of the modeling and analyses activities for this study. The tasks will be completed by the principal investigators listed on this work plan and their designees.

- Perform preliminary scoping calculations to determine important parameters for test. Investigate analytical model of Philip (1998) as a tool.
- Construct numerical model of flow through the test cell.
- Perform simulations of flow using dual-continuum models and compare to experiments. Refine models and parameters as tests evolve.
- Compare predictions to test results and provide assessment of current modeling approaches.

3.5. Special Considerations

None.

4. TRAINING

Personnel who will perform quality-affecting activities under this TP will have completed required training based on the SNL OSTI Training Matrix. The SNL QA Lead is responsible for ensuring that training is completed.

HEALTH AND SAFETY

The following Primary Hazard Screening (PHS) documents are completed for the X-Ray Imaging Laboratory and the Flow Visualization and Processes Laboratory:

- PHS Number SNL7A00086-001, X-Ray Imaging Laboratory

- PHS Number 979851437-001, Flow Visualization and Processes Lab: General Operations

The hazard classification for these laboratories is LOW. In general, hazards associated with activities described in this test plan include:

- standard shop hazards,
- power hand tool hazards from machine shop and hand power tools,
- electrical hazards from light sources used for photo documentation,
- radiation exposure through the use of the X-ray lab, and
- pressure hazards from vacuum chambers.

Laboratory personnel will receive the appropriate training as required in the PHS documents before performing any laboratory operations.

Safety requirements will not impact the conduct or results of the activities performed under this test plan.

5. PERMITTING/LICENSING

There are no special permitting or licensing requirements for the work described in this test plan.

6. QUALITY ASSURANCE

The following procedures will be implemented for work described in this test plan:

- QAP 1-1 Organization and QA Program
- QAP 2-1 Qualification and Training
- QAP 4-1 Procurements
- QAP 6-1 Document Review Process
- QAP 6-2 Document Control Process
- QAP 9-1 Analyses
- QAP 12-1 Control of Measuring and Test Equipment
- QAP 13-1 Sample Control
- QAP 16-1 Corrective Action
- QAP 17-1 Records
- QAP 19-1 Software Requirements
- QAP 20-1 Test Plans
- QAP 20-2 Scientific Notebooks

Documentation pertaining to these experiments will be organized as a records package that will include scientific notebooks. In addition, records may include electronic files, data sheets, and data logs, which will provide the following documentation, as applicable:

- planning documents
- personnel qualification and training records
- methods and procedures including details of repetitive activities (i.e., ion probe calibration, X-ray image acquisition, X-ray image digitization)
- equipment descriptions (e.g., model and serial numbers, specification sheets)
- calibration records
- sample preparation and control documents
- documentation of in-house FORTRAN codes including verifications and copies of codes
- sample descriptions
- sample characterization (e.g., measured porosity, permeability, formation factor)
- preparation and evaluation of brine/tracer solutions
- sample saturation data
- measured mass of fluids circulated
- measured tracer concentrations
- routine calculations (e.g., sample porosity, diffusion rate calculations)
- pressure measurements and data plots and tables
- electronic files used to produce image based data (see Table 3),
- documentation of data analyses, and
- evaluations of X-ray imaging techniques
- assessments

Developed X-ray film will not be submitted as a QA record as the film degrades over time. Instead, data files of digitized X-ray images (see Section 3, Table 3) will be maintained and submitted on electronic media. The developed X-ray film will be maintained until the records package has been submitted to the OSTI Records Center.

Software will be qualified and documented in accordance with QAP 19-1 Software Requirements. All qualified software shall be controlled by the OSTI Software Configuration Management process.

Other QA records will be submitted to the OSTI Records Center as required by the applicable OSTI QA Procedures and QAP 17-1.

7. REFERENCES

Altman, S. J., M. Uchida, V. C. Tidwell, C. M. Boney, and B. P. Chambers. 2004. Use of X-ray Absorption Imaging to Examine Heterogeneous Diffusion in Fractured Crystalline Rocks. Journal of Contaminant Hydrology **69**:1-26.

Birkholzer, J; Li, GM; Tsang, CF; Tsang, Y. 1999. Modeling studies and analysis of seepage into drifts at Yucca mountain, Journal of Contaminant Hydrology **38**:349-384.

Detwiler, R. L., S. E. Pringle, and R. J. Glass. 1999. Measurement of fracture aperture fields using transmitted light: An evaluation of measurement errors and their influence on simulations of flow and transport through a single fracture. Water Resources Research **35**:2605-2617.

Flint, L. E. 2003. Physical and hydraulic properties of volcanic rocks from Yucca Mountain, Nevada. Water Resources Research **39**:1119.

Philip, J. R.. 1998, Seepage shedding by parabolic capillary barriers and cavities, Water Resources Research **34**:2827-2835.

Tidwell, V. C., and R. J. Glass. 1994. X-Ray and Visible-Light Transmission For Laboratory Measurement of two-Dimensional Saturation Fields in Thin-Slab Systems. Water Resources Research **30**:2873-2882.

Tidwell, V. C., L. C. Meigs, T. Christian-Frear, and C. M. Boney. 2000. Effects of spatially heterogeneous porosity on matrix diffusion as investigated by X-ray absorption imaging. Journal of Contaminant Hydrology **42**:285-302.